VII. Diagnostics

Diagnostic devices are employed in the antiproton source to provide a means of sensing the beam in each of the machines and transport lines. With the low intensity pbar beams, some special devices and modifications were developed to detect the weak signals in a non-destructive manner. Most of the diagnostic devices found in the antiproton source can also be found in other accelerators.

A. DCBCT's

A DCBCT or Direct Current Beam Current Transformer is a device used to measure the quantity of circulating beam with high precision. D:IBEAM and A:IBEAM, the beam current or intensity readbacks for the Debuncher and Accumulator respectively, are sourced from such a device installed in each ring. Accuracy is one part in 10^5 over the range of 3 mA to 85 mA of beam current. As an aside, the revolution period of both the Debuncher and Accumulator for an 8 GeV particle is ~1.6 μs. Based on this coincidence with the units of charge, beam current can easily be converted to intensity:

$$1\ mA = 1 \times 10^{10}\ particles.$$

because

$$\frac{1.6 \times 10^{-19}\ \text{Coulomb/particle}}{1.6 \times 10^{-6}\ \text{second}} = 1 \times 10^{-13}\ \text{Amperes/particle}$$

If there are 10^{10} circulating particles, then the current is:
1×10^{-3} Amp or 1 mA.

The pickups are supermalloy tape-wound toroidal cores with laminations, which act to reduce eddy currents. Beam goes through the hole of the donut and acts as a single turn on the toroid transformer. The beam sensing electronics are attached to wire windings on the toroids. Passing beam induces currents in the toroids and the electronics sense those currents and produces an equal and opposite current that keeps the net toroid current at zero. Referring to figure 7.1, T1 senses the AC portion of the beam while T2, T3, the modulator, and demodulator sense the DC portion. The DC and AC signals are summed in OP1, which drives each toroid just hard enough to cancel the beam-induced currents. T4 and OP2 sense modulator ripple and anything else the OP1 feedback loop may have missed and compensates for it. OP3 measures the drive produced by OP1 and OP2, which is proportional to the beam intensity. The beam signal is actually measured across the resistor R, which resides in the temperature-controlled current to voltage converter upstairs in AP10. The accuracy of the measurement is dependent on the resistance staying constant. An OMEGA temperature controller maintains the resistor's temperature at 100° Fahrenheit. The controller contains an EPROM to retain the last set values in the event of a power failure.

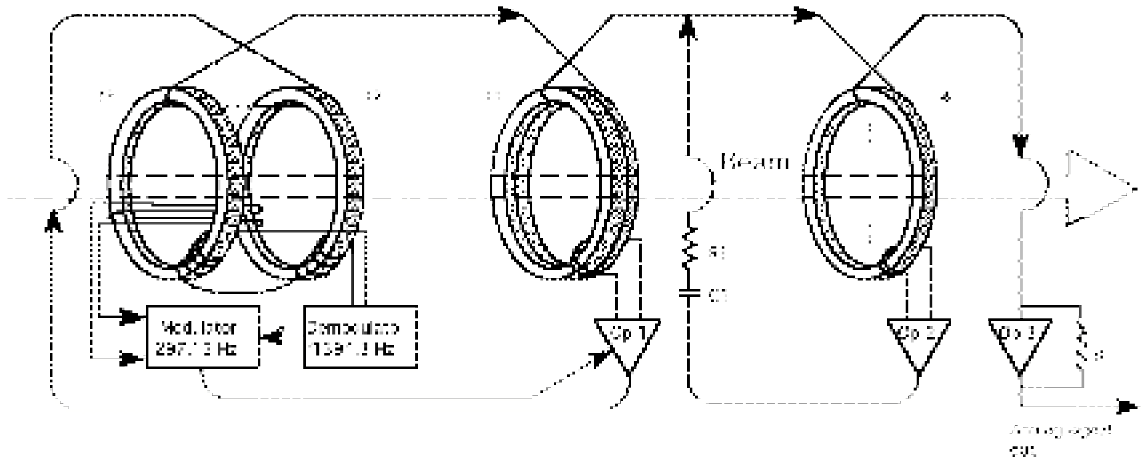

Figure 7.1 IBEAM Direct Current Beam Current Transformer

The DCBCT toroids are contained in 40 inch long by 10 inch diameter structures that reside in straight section 10 of both machines. The signal goes upstairs to AP10 and eventually to Keithley digital voltmeters located in racks in the AP10 control room. A test current can be used to provide 1.2 mA that appears as 1.2 X 10^{10} particles on the IBEAM readback. The switch for the test current is located on the current to voltage converter in the upstairs electronics rack.

B. Beam Position Monitors

The Pbar Beam Position Monitor (BPM) system provides single turn and multi-turn or closed orbit position information with sub-millimeter resolution. Position information is used to correct the orbit and to measure lattice parameters. The Debuncher has 120 sets of pickups and the

Accumulator has 90. They are split-plate, bi-directional electrostatic pickups that are sensitive to a Radio Frequency (RF) structure on the beam, therefore the beam must be bunched for the BPM's to work. Pickups are generally found at quadrupole locations in the lattice. Circular and rectangular pickups are used depending on location; the beam pipe size is small in low dispersion sections and is very large horizontally in areas of high dispersion. Rectangular pickups are used only in the high dispersion sections of the Accumulator. Accumulator high dispersion BPMs are 10 x 30 cm rectangles, Accumulator low dispersion BPMs are cylindrical and have a 13 cm diameter, Debuncher BPMs are cylindrical with an 18 cm diameter. BPMs can also be found in the AP1, 2 and 3 beamlines. Beamline BPM's are located at quadrupole locations and are of the semi-circular design.

1. Debuncher

For the Debuncher system, signals from the pickups are amplified with preamps, which are mounted directly on the beam pipe. There is also a second pair of amplifiers with 46 db of gain that can be switched in. Power supplies for the amplifiers are located upstairs in the service buildings in the BPM racks. Preamp outputs are fed via 1/8-inch hard line to Trontek gain switchable amplifiers that are mounted on the tunnel wall. Trontek amplifiers are also used on Debuncher and some AP-2 BPM's. The Trontek's

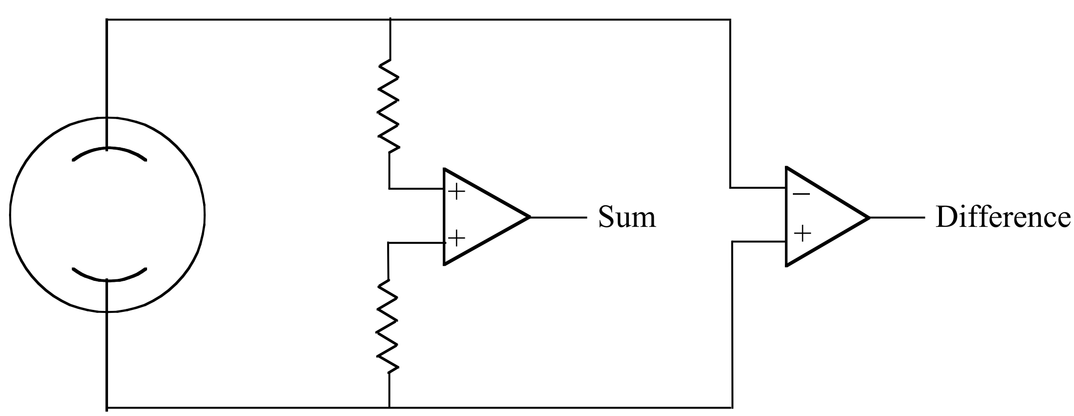

Figure 7.2 Debuncher pickups

have a 20 db and a 40 db amplifier that are selectively switched in line to provide 0, 20, 40, or 60 db gain.

After amplification in the tunnel, the sum and difference signals (see figure 7.2) travel on 3/8-inch heliax to the inputs of the multiplexers upstairs in the service buildings. These multiplexers, which are remnants of the old Main Ring BPM system, have ten inputs. There are two vertical and two horizontal muxes at each service building for the Debuncher. The multiplexer selects one pickup signal per sample period and sends it to the RF modules. A closed orbit measurement is typically the average of 20 individual measurements.

The next set of electronics is one of two types of RF module. The 53 MHz (fast) Tevatron-type module is used to provide turn-by-turn information. The slow RF modules are used for closed orbit information. The Debuncher BPM system has a single Voltage Controlled (X)crystal Oscillator (VCXO) at AP10 which runs at 10 kHz above the harmonic frequency (2.36 MHz) seen by the RF modules. The beam signal and VCXO are mixed to produce a 10 kHz signal, which the op amps in subsequent electronics are able to handle. The VCXO output is split three ways to go to AP10, AP30, and AP50. Once in the building the signal splits again to RF modules at opposite ends of the

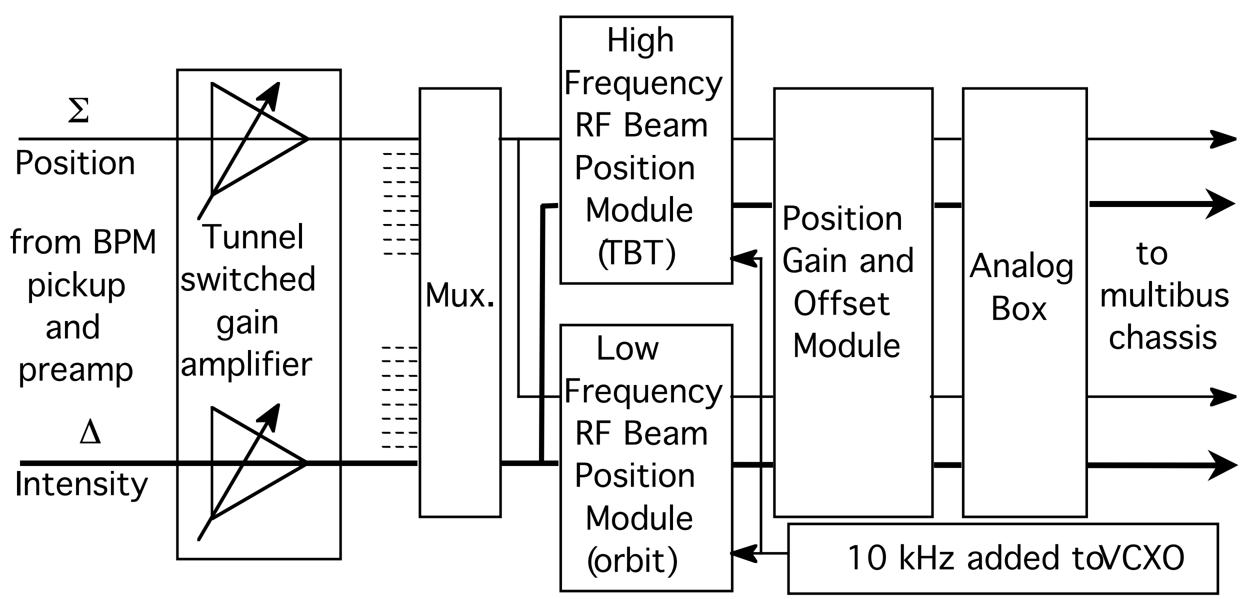

Figure 7.3 Debuncher BPM block diagram

building. The VCXO is tuned over a small range to center the BPM signal in the passband of the filters in the next electronics module. Figure 7.3 provides a generalized BPM block diagram for the Debuncher system.

2. Accumulator

An upgrade to the Accumulator BPM system was finally completed late in 1998. Most changes involved the signal processing and communication hardware, including the use of a VXI platform instead of CAMAC. Both the analog and digitizer VXI cards were designed and built at Fermilab. The beam detectors and preamplifiers remain unchanged from the original system.

Signals from the BPM pickups are amplified by a preamplifier mounted to the beampipe. There are A and B signals corresponding to the two BPM pickup plates. The matched signal paths have independent gain control, in both cases the output of the preamp provides the input for the analog card. This scheme is different from the old Accumulator system and present Debuncher system. Previously sum and difference signals were created by electronics in the tunnel, now the signals are processed in the service buildings. Because the signal strengths from the two pickups are so similar, the cables connecting to the analog card must be precisely matched. Any modification to one of the signals as it travels to the analog card will result in errors in the calculated position.

The analog card has eight inputs made up of four channel-pairs. Each input is gain adjustable with two modes for Turn-By-Turn (TBT) or closed orbit operation. Output from the analog card becomes the input for the digitizer card. The digitizer card also has eight inputs made up of four channel-pairs. Each input provides a 12-bit digitizer and a 128k buffer. The digitizer card has an on-board Digital Signal Processor (DSP) which processes the digitized data. When in TBT mode a position for each turn is calculated, in closed orbit mode an average position is calculated.

The original Accumulator BPM system made use of a reference oscillator signal from an output of the ARF3 low level. With the new system, the expected revolution frequency of the beam is an ACNET device that is set by the user.

In addition to their primary role of detecting beam position, the Accumulator BPM plates also are used as a mechanism to remove trapped

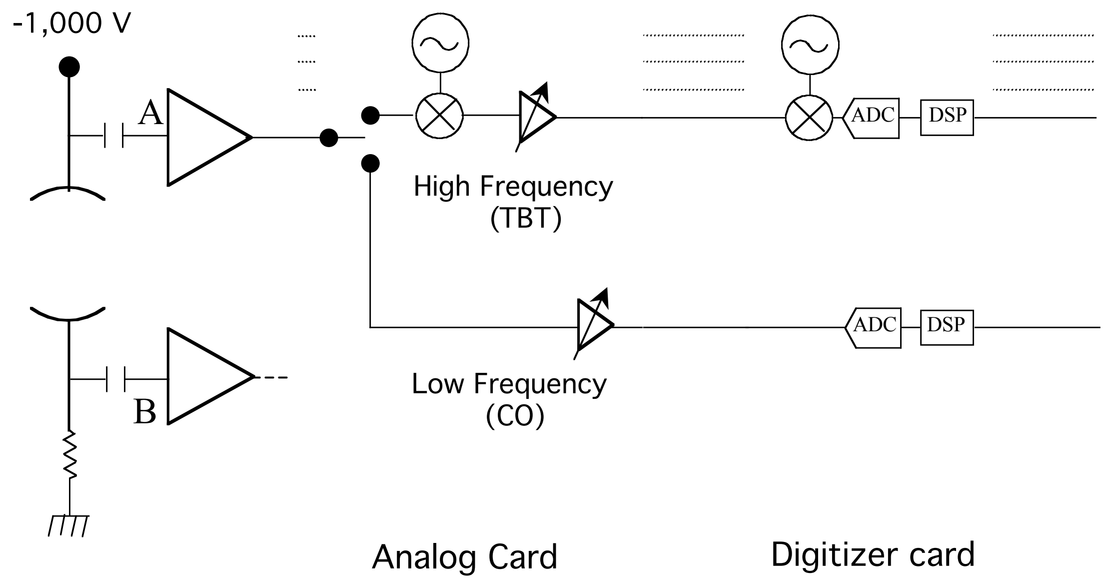

Figure 7.4 Accumulator BPM Box Diagram

positive ions. A –1,000 Volt DC “clearing voltage” is applied to the pickup plates to attract ions. The RF BPM signals are passed to the electronics through blocking capacitors (see figure 7.4).

3. Transport Lines

In the transport lines, amplifiers are used on some of the AP-2 line BPM's to boost the weak signals produced due to the low intensity. When stacking, the number of antiprotons and other negative secondaries (mostly pions) is relatively small, on the order of 6 x 10^9. The beam intensity in the D to A line is even smaller, 10^8 or less, so D to A line BPM's are not reliable when stacking. In the other transport lines, BPM's can be very useful. The primary advantage of BPM's is that they are passive, they do not make direct contact with the beam.

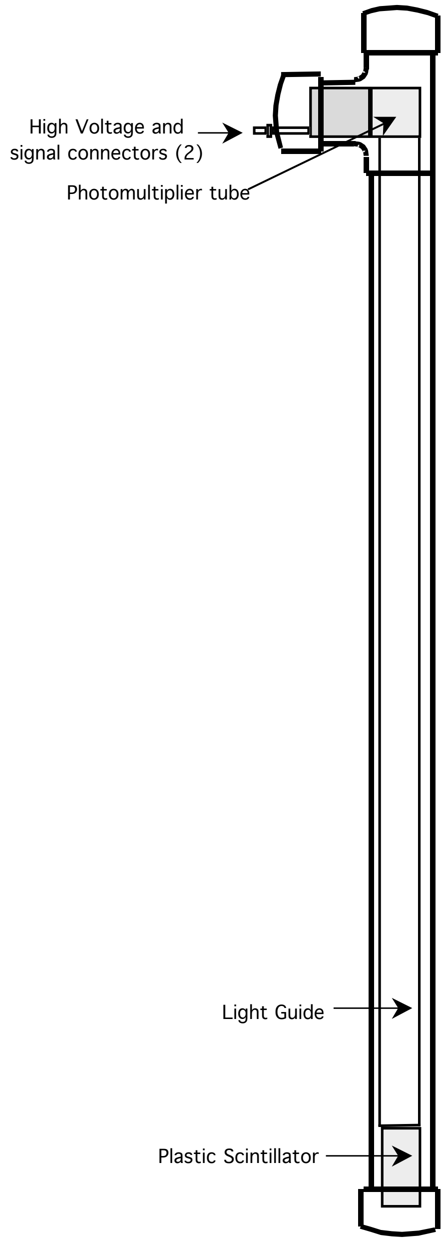

Figure 7.5 Accumulator and Debuncher BLM

C. Loss Monitors

There are two types of Beam Loss Monitors (BLMs) in the antiproton source, ion chamber and plastic scintillator with a photomultiplier tube (PMT). The ion chamber BLMs can be found in beamlines and are used to monitor losses during stacking and pbar transfers. The plastic scintillator BLMs are distributed throughout the Accumulator and Debuncher rings and can be used for studies or for locating loss points.

The ion chamber monitors are of the same type as those used in the Tevatron. The BLM detector is a sealed glass ion chamber with a volume of 110 cubic centimeters that is filled to 1 atmosphere with Argon. A high voltage power supply is daisy chained to a string of BLMs and provides about a 2,000 Volt bias to the chamber. The output goes upstairs on an RG58 signal cable to a beam loss integrator and then to a Multiplexed Analog to Digital Converter (MADC). The MADC is read by the controls system in the usual way.

A "paint can" style BLM was formerly used in the antiproton source for both the beamlines and rings. They were made up of a photomultiplier tube immersed in scintillating oil. Because the scintillating oil is categorized as hazardous waste, an effort was made to replace the paint cans. The plastic scintillator design BLM retains the sensitivity to small numbers of particles, which the ion chamber loss monitors don't have. The loss monitors are made up of a 4"x2"x$^1/_2$" piece of plastic scintillator glued to a 36" long Lucite light guide (see figure 7.5). At the end of the light guide a small Lucite coupling attaches it to an RCA 4552 PMT. The PMTs were recycled from the old paint cans and are relatively rugged. The intent of the light guide is to keep the scintillator near the magnets but to extend the phototubes up and away from the region of beam loss. This assembly is mounted in a housing made up of PVC pipe and has feed-throughs for the high voltage and signal cables.

High voltage supplies for the BLMs are located in the AP10, 30 and 50 service buildings. Each supply feeds up to 20 BLMs through a Berkeley voltage divider which allows the gains of all the PMT's to be matched by setting the high voltage to each one individually. In actual practice all of the high voltages are run near maximum value.

The BLM output goes to a quad or octal discriminator, which handles four or eight BLMs. It levels the signal spike from the PMT caused by the lost particle and sends a NIM level pulse to a Jorway quad scalar which handles four BLM's. The scalar is really a pulse counter that counts pulses during the gated period defined by the gate module. A CAMAC 377 card provides start and stop times to the gate module for the gate pulse. Output from the Jorway 84-1 card is sent to the controls system. Plastic scintillator loss monitor electronics count pulses while Tevatron style argon gas loss monitor electronics accumulates charge on an integrator capacitor.

D. Secondary Emission Monitor (SEM) Grids

SEM grids are used to measure the beam profile in the horizontal and vertical planes. SEMs consist of 30 vertical and 30 horizontal titanium strips placed in the path of the beam. Beam particles have elastic collisions with electrons in the strips and dislodges them (see figure 7.6). This causes a current to flow in the strips and sensitive preamplifiers connected to each strip detect this current. For every forty protons or antiprotons passing through the SEM, one electron is dislodged yielding a detector efficiency of 2.5%. A clearing voltage of +100 VDC can be applied to foils placed before and after the strips to improve the work function of the titanium and double the efficiency to 5%. Since some of the beam collides with the titanium strips, SEM grids are not passive devices. Most SEM grids are located in the

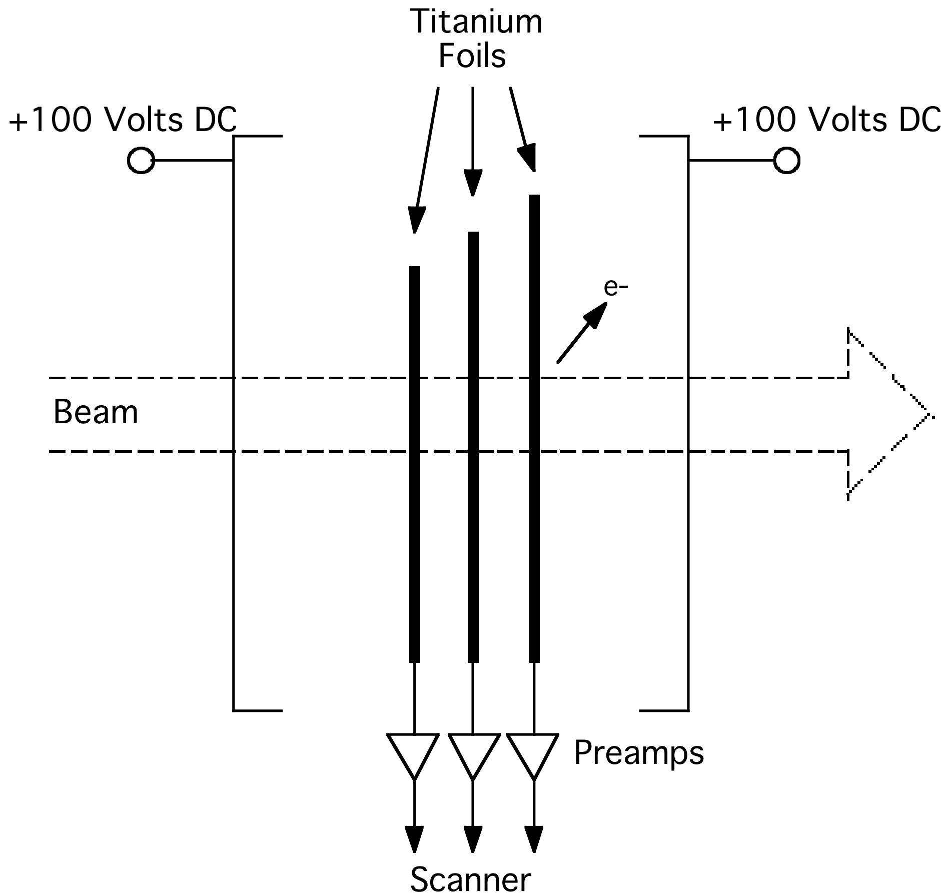

Figure 7.6 SEM grid

transport lines although a few are located near injection and extraction points in the rings to be used during initial tune-up. If one of the ring SEM grids is left in, beam will be rapidly lost.

Motors move the grids for one plane or the other into the beam and are controlled by a CAMAC 181 card. The SEM motor controllers have a safety system input. It retracts the SEM grids from the beam pipe when the beam permit is down. This feature is intended to keep the grids out of the beam pipe should vacuum be broken. Technicians can override this function locally if necessary.

The SEM grids operate at beam pipe vacuum pressure and thus have no gas gain like the Segmented Wire Ionization Chambers (SWICs) found in Switchyard. Preamp boxes are used to amplify the signals generated by the SEM. Preamp boxes contain a pair of mother boards with 30 preamp boards plugged into each (one horizontal and one vertical set). Some versions of the preamp box have charge splitters that when selected attenuates the signal to the preamp 15 times when the charge split input is +5V. D to A line SEMs use preamps that are 260 times more sensitive than those for the other SEMs due to the low beam intensities found during stacking.

Switchyard style SWIC scanners are used for scanning the SEM wires. A

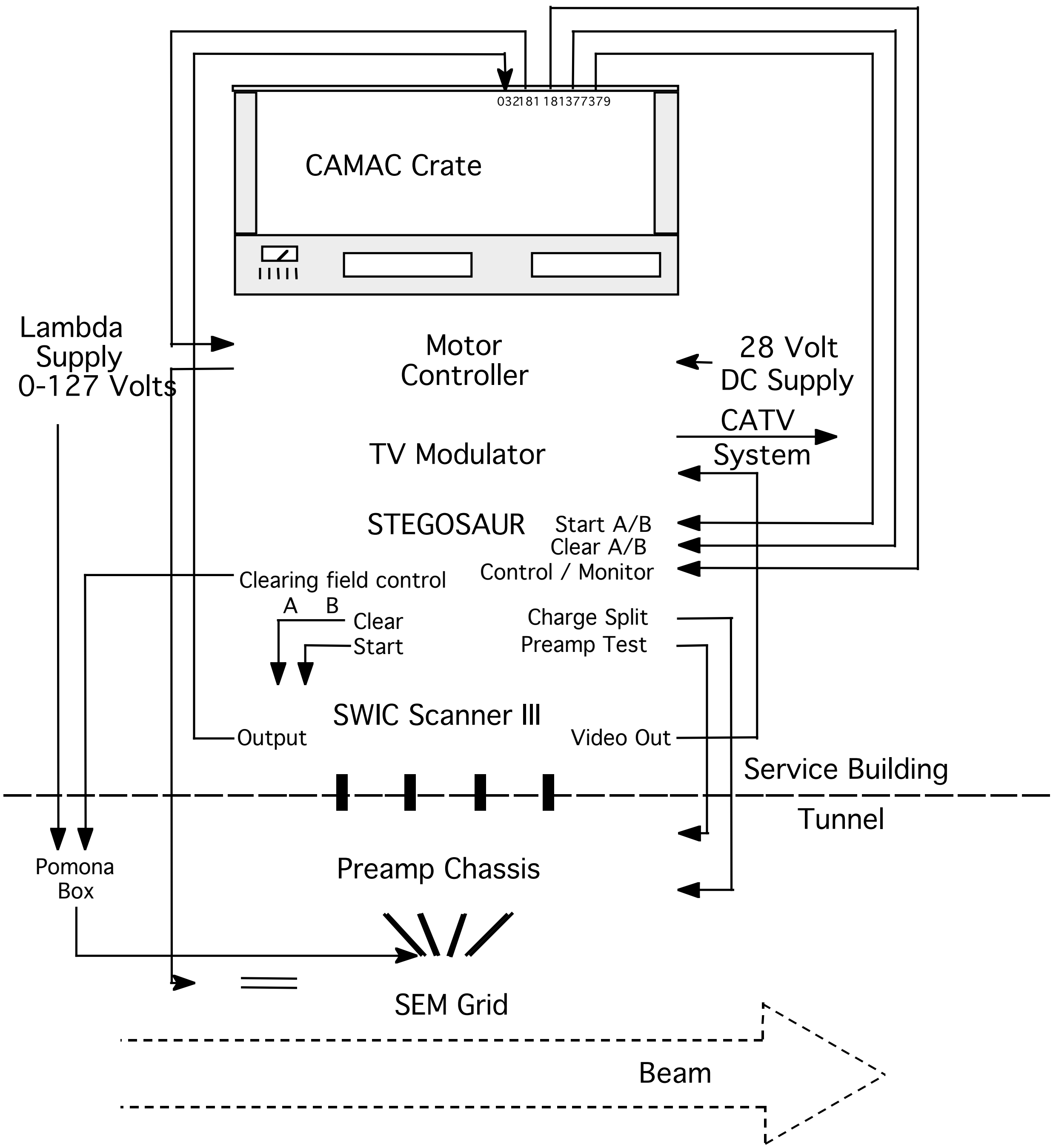

Figure 7.7 SEM block diagram

scanner is made up of: a Z80 based microprocessor, memory and support chips, FET switches and three amplifiers. Scanners receive "clear" and "start" timing and interface with a CAMAC 032 module for communication with the control system (see figure 7.7 for a block diagram of the SEM electronics). The SWIC scanner also has a video output, which goes to modulators upstairs for distribution on the cable TV system. SWIC scanners read the charge accumulated on the sixty integrators tied to thirty horizontal and thirty vertical SEM strips.

SEMs are triggered by STEGOSAURs otherwise known as SEM Test Event Generators (the OSAUR was added to STEG to make it pleasing to the ear). STEGs provide fanout of CLEAR and START timing and test pulsing for up to six SEM grid scanners. Since six SEM grids can be scattered over a long beam line or over adjacent beam lines like AP2 and AP3, STEGs provide an A and B set of clear and start times. The clear time is normally initiated by a CAMAC 377 timer card triggered by a TCLK event. It occurs at least 50 milliseconds before the start trigger. The start time is generally initiated by a CAMAC 379 timer card triggered by a Main Injector Beam Sync (MIBS) event since close synchronization with the beam is necessary (the exception is the Debuncher to Accumulator transfer, which is not synchronized to the Main Injector).

Other functions of a STEGOSAUR are to synchronize preamp test pulse timing, clearing field control, and charge splitter control for the SEM grid scanners. Control is provided by a CAMAC 181 card. The preamp test is used to test the connection between the preamp chassis and the scanner by connecting a fixed signal to all of the strips on the SEM grid. The clearing field control checks that the foil strips are correctly clearing charge shortly before the start time goes out, this will not alter the display of a SEM that is working correctly.

E. Scrapers

Scrapers are devices that can be used to block off part of the accelerator aperture. A physical analogy would be a gate valve in a water line. The scraper could be used to trim the halo off of the beam, to measure the acceptance of the machine, or to define the emittance of the beam. There are presently ten scrapers in the pbar source:

D:RJ306: Debuncher horizontal (Right Jaw) scraper. It enters the beam from the inside of the ring. It is adjacent to D3Q7.

D:TJ308: Debuncher vertical (Top Jaw) scraper. It enters the top of the ring, traveling 1 7/8 inches. It is located adjacent to D3Q8.

D:RJ410/D:LJ410: Debuncher momentum scrapers. These are horizontal scrapers that are placed in a high dispersion region to allow one to measure the momentum spread, DP/P, of the beam. They are located between D4Q10 and D4Q11.

A:RJ500/A:LJ500: Accumulator horizontal scrapers. They enter the beam from the inside and outside of the ring. They are located near A5Q1.

A:TJ307/A:BJ307: Accumulator vertical scrapers. They enter the beam from the top and bottom of the ring. They are located adjacent to A3Q7.

A:RJ314/A:LJ314: Accumulator momentum scrapers. They are horizontal scrapers in a high dispersion region. They are located in the center of the A40 straight section.

Scrapers are moved with stepping motors and the scraper position is determined with a Linear Variable Differential Transformer (LVDT). Stepping motors allow small and fairly precise position changes. An LVDT puts out a voltage proportional to the position of a slug within a ferrite cylinder with a series of windings. The controlling electronics for the stepping motors are located in the AP-30 and AP-50 service buildings, two CAMAC 057 cards are used to control them. Each scraper has a motor controller card (just like Switchyard septa have). A brown lambda supply provides +24 volts for the motor and +/-15 volts for the LVDT on each scraper.

Incidentally, there are a number of other moveable devices scattered around both pbar rings that operate on the same principle. These devices are normally moved to either electrically center them (as in stochastic cooling tanks), to improve the aperture (Diagnostic devices) or to provide an orbit bump (dipoles that can be rolled and quadrupole magnets that can be moved vertically). For example, the Debuncher Schottky pickups are moveable. They have an "MS" prefix for "Moveable Stand" and have the cryptic ACNET names:

D:MSSCV1 Vertical Schottky Stand
D:MSSCH1 Horizontal Schottky Stand

F. Collimators

Much like their scraper counterparts in the rings, collimators are used to skim the halo off the beam, define the emittance of the beam, and measure the acceptance of a beam line. Although the devices themselves are virtually the same, a scraper is found in an accelerator and a collimator is found in a beam line. All of the collimators are located in the AP2 line and use the same type of electronics as the scrapers. The CAMAC 057 control card and the motor controllers are located in the AP0 service building.

There are two sets of horizontal, two sets of vertical and one set of momentum collimators in the AP2 line. All are of similar construction. The momentum collimator is placed in the left bend section of the beamline where the horizontal dispersion is high. The magnets and collimator act like a mass spectrometer. The ACNET collimator names are:

D:RJ707/D:LJ707: Right and Left Jaw (as you face the Debuncher) of a horizontal collimator placed just downstream of IQ7.

D:TJ708/D:BJ708: Top and Bottom Jaw of a vertical collimator placed just downstream of IQ8

D:RJ709/D:LJ709: Another horizontal collimator located just downstream of IQ9.

D:TJ710/D:BJ710: Another vertical collimator located just downstream of IQ10.

D:RJ719/D:LJ719: The jaws for the momentum collimator located in the middle of the dipoles that make the left bend, just downstream of IQ19.

G. Toroids

Pearson single turn large aperture toroids are located in the transport lines to monitor beam intensity. They are beam transformers that produce a signal that is proportional to the intensity (1V for every 1A of current). The toroids make use of integrators that sample over a gated period that is defined by an MRBS timer. M:TOR109, for example, uses the timing event

M:TR109S to start the sample period. The output of the integrator is sampled and held for an A/D conversion.

M:F16TOR is located in the P2 line and is used to monitor beam intensity entering the line during a pbar transfer. It was originally used for measuring beam entering the Main Ring and the gating was set up to sample the pbars on the first turn. The gate is now wide enough to sample a full Booster batch of 84 bunches. However, the readback saturates at an intensity of 2E11 so it is not useful during stacking.

M:TOR105 is located in the Pre-Vault enclosure just upstream of P6QA and is used to monitor proton or antiproton intensities in the AP-1 line. M:TOR109 is also in the Pre-Vault enclosure just upstream of the target vault, and gives a good indication of the number of protons entering the vault and striking the target.

D:TOR704 is located just downstream of the vault and measures the flux of negative secondaries, most of which are negative secondaries other than pbars, entering AP-2. There is another toroid at the end of the AP-2 line, D:TOR733. Like TOR704, TOR733 will measure all of the negative secondaries passing through, whether pbars or not. Unfortunately the beam intensity in the AP-2 line during stacking is too low for the toroids to be an effective diagnostic.

There is one toroid located in the AP-3 line, D:TOR910, which is located between EQ10 and EQ11. This toroid is used both to measure reverse injected protons directed down the AP-3 line and also for measuring pbars extracted during a shot.

Originally there were toroids located near the IQ17 and IQ28 quadrupoles in the AP-2 line and the TQ6 quadrupole of the D/A line. They were removed due to lack of use and to open up the aperture by removing the restricted beampipe that they surround. There is also a toroid 100 in the AP-1 line, but it is no longer connected.

H. Ion Chamber

There is only one ion chamber in use in the antiproton source and that is D:IC728. This ion chamber is located downstream of IQ28 and is used to measure the flux of negative secondaries near the end of the AP-2 line during stacking cycles. Most of the negative secondaries are not pbars but the total flux should still give an approximate indication of the pbar intensity.

The ion chamber has a high voltage electrode at -300V and a signal electrode contained in a chamber filled with helium gas. Secondary particles traveling down the AP-2 line pass through the chamber and ionize the helium resulting in a current path to the signal electrode. The result is a signal proportional to the beam intensity.

A small amount of helium passes out of the ion chamber through a bubbler, however the loss rate is very small. Helium bottles for D:IC728 are found in the AP50 service building. The signal from the ion chamber is digitized and sent to a scalar card. There is a start and clear time used to gate the scalar card. The start time (D:IC728S) is provided by a CAMAC 379 card referenced to an MIBS timer and the clear time (D:IC728C) is provided by a CAMAC 377 card using a TCLK reference.

An ion chamber is able to measure smaller beam currents than a toroid so it is an appropriate choice for the AP-2 line. Ion chambers also formerly existed at the upstream end of the AP-2 line (D:IC704) and in the D/A line (D:IC806) but both were replaced with toroids. The ion chambers have a tendency to leak gas into the beampipe so all but D:IC728 were removed. Unfortunately the toroids that replaced them have difficulty resolving the small beam intensity.

I. Schottky Signals

A charged particle passing through a resonant stripline detector or a resonant cavity creates a small signal pulse known as a Dirac pulse. A particle beam is made up of many charged particles and creates a signal called Schottky noise. Schottky noise is a collection of signal pulses in the time domain, which corresponds to a spectrum of lines in the frequency domain. The lines occur at harmonics of the revolution frequency since the particles circle the accelerator and pass repeatedly through the pickup. The combined response from all the particles in the ring is smeared over a finite frequency range (Schottky bandwidth) at each harmonic. This frequency range is related to the momentum spread of the beam by

$$\frac{df}{f} = \frac{dp}{p}\eta$$

where η (eta, the slip factor) is fixed by the machine lattice (-.012 for the Accumulator, -.006 for the Debuncher).

The revolution period of beam in the Debuncher is 1.695 μs, therefore the revolution frequency is 590,035 Hz or .590035 MHz. In the Accumulator the revolution period of the beam varies between 1.5904 μs at the injection orbit to 1.5901 μs at the core. This corresponds to revolution frequencies of .628766 MHz and .628881 MHz respectively. The Debuncher revolution frequency is lower than that of the Accumulator because the Accumulator has a smaller circumference.

Signals from the Schottky detectors can be displayed on signal analyzers. A coaxial relay mux (the mux box) at AP10 has eight inputs and eight outputs (not all are used) and is used to remotely connect a signal of interest to one of the analyzers. There are six Schottky detectors, which can connect to one of the four spectrum analyzers (analyzer #3 is always connected to the Accumulator longitudinal schottky) via the mux box.

Schottky pickups (or detectors) are devices that are used to detect Schottky noise. There are six Schottky pickups used in the Antiproton Source. The Accumulator and Debuncher each have vertical, horizontal, and longitudinal pickups in the 10 straight section. The vertical and horizontal

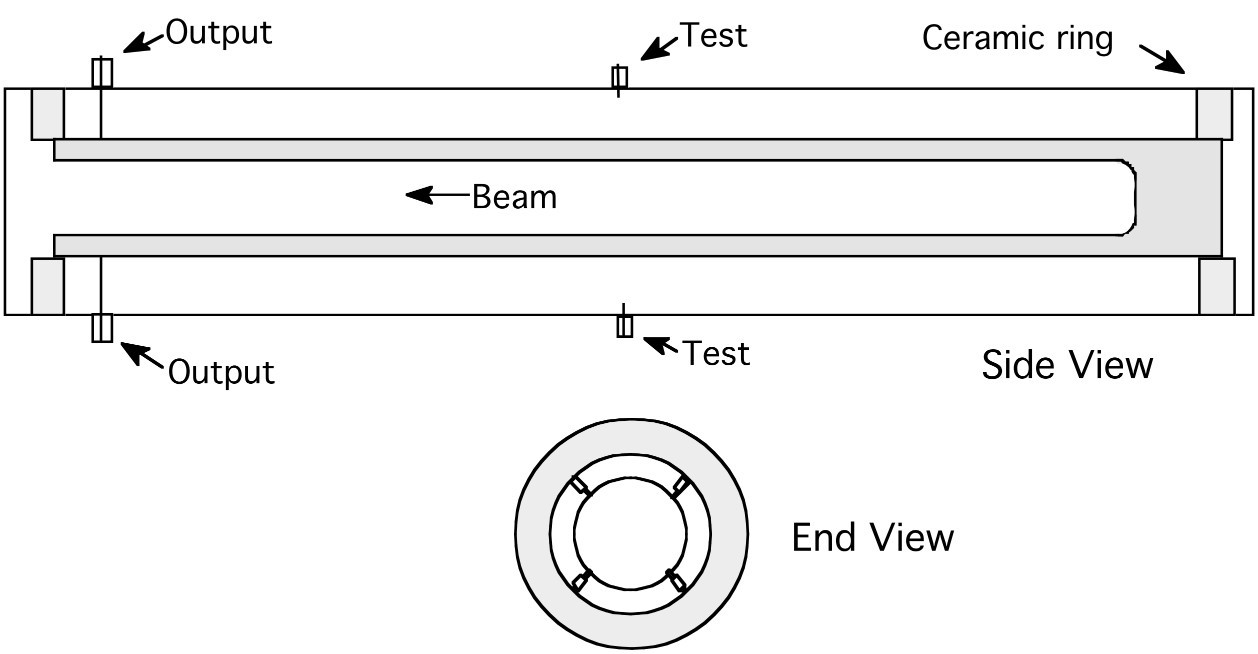

Figure 7.8 Vertical Schottky pickup

transverse pickups are approximately 24 inches long and 2 inches in diameter. These pickups detect transverse beam oscillations. The vertical pickup has the striplines above and below the beam with outputs on the top and bottom, the horizontal pickup is rotated 90°. The transverse pickups are a stainless steel tube with a slot cut along much of the long dimension (see Figure 7.8). The pickup is held by ceramic rings, which also electrically insulate it from the outer housing.

Signals from each plate are fed through to a 3/8-inch heliax cable, which is run to the AP-10 service building. Signals are not run directly to the MCR because of the signal loss that would result from the long cable run. The detectors resonate at a frequency determined by the length of the strip inside the cylinder plus the coaxial cable between the output connector and a capacitor. Connectors in the middle are used to inject a signal for tuning the device to the frequency of interest. Horizontal and vertical pickups are mounted on motorized stands so that the device can be centered with respect to the beam.

The longitudinal pickups are larger, 37 inches in length and 3.4 inches in diameter. These pickups are tuned quarter-wave cavities that are made by separating a stainless steel tube into two sections with a ceramic across the gap. Charged particles crossing the gap produce Schottky signals. The longitudinal detectors are tuned with plungers or sliding sleeves on the center element. Again, the unused fittings seen on the cavities are used to inject signal for tuning purposes.

The Schottky detectors used in the Antiproton Source are designed to be most sensitive to the 126th harmonic of the beam's revolution frequency. Although signals at or around the 126th harmonic are usually the strongest in these detectors, signals for other harmonics can also be detected. The Schottky signals weaken as you get further away from the 126th harmonic.

There are several reasons for choosing the 126th harmonic for the design of the Schottky detectors. The spectral power contribution from the 53.1 MHz bunch structure (from ARF-1 in the Accumulator) is minimized by using a frequency located between 53.1 MHz (h=84) and its second harmonic at 106.2 MHz (h=168). The resulting signal from the revolution harmonic for the Accumulator core would be 126*.628881 MHz = 79.239 MHz. The physical size of the detector must also be taken into account. The aperture must be large enough to not restrict beam transmission. Limited space available in the rings limits the pickup length to only 1 or 2m. Schottky detectors designed for the 126th harmonic fit both of these size constraints. For example, recall that the longitudinal Schottky pickups are 1/4 wavelength long. The physical length of the cavity as built is .94 meters ($\frac{1}{4*126}$ of the Accumulator circumference) which would result in a resonant frequency of:

$$f = \frac{\text{velocity}}{\text{length}} \sim \frac{3E8 \text{ m/s}}{4 * .94 \text{ m}} \sim 79.75 \text{ MHz.}$$

That works well for the Accumulator, but the Debuncher h=126 falls at 74.34 MHz (126 * .590035 MHz) so a tuning screw is added to its longitudinal pickup to capacitively lower the resonant frequency of the cavity.

Schottky pickups have many diagnostic uses. They are used to measure the betatron tune, synchrotron frequency, transverse emittance and momentum spread. They can also be used to accurately measure small beam currents. The DCBCTs have an accuracy of about ±2nA. The Schottky pickups can be calibrated against the DCBCTs at beam currents up to around 100 mA and the spectrum analyzers will hold accuracy for smaller currents than the DCBCT. The spectral power of the signal is proportional to the number of particles in a DC beam.

J. Signal Analyzers

1. Spectrum analyzers

Spectrum analyzers are used in the Antiproton Source to study the frequency domain of the beam. A spectrum analyzer is a swept-tune superheterodyne receiver that provides a Cathode Ray Tube (CRT) display of amplitude versus frequency. In the swept tune mode the analyzer can show the individual frequency components of a complex signal. The spectrum analyzer can also be used in a fixed tune or "zero span" mode to provide time domain measurements of a specific frequency much like that of an oscilloscope. Note that a spectrum analyzer does not provide any phase information.

A superheterodyne receiver is a common type of radio receiver that mixes an incoming signal with a locally generated signal. The output consists of a carrier frequency that is equal to the sum or difference between the input signals (but no information is lost). The carrier signal is known as the Intermediate Frequency (IF) signal.

In a spectrum analyzer, the incoming signal is mixed with a programmable Variable Frequency Oscillator (VFO) producing carrier frequencies containing the two original signals and signals at the sum and difference of their frequencies. All but the sum or the difference signals are filtered out. The filter output is the IF signal which can be processed for display. The spectrum analyzer uses the VFO to define the frequencies to be analyzed (center frequency and span) and the sample rate (sweep time, resolution bandwidth).

1. Network analyzers

Network analyzers are used to study transfer or impedance characteristics of systems. A reference signal is injected into a system under test and the output of the system is displayed on a CRT (see figure 7.9). Although less expensive analyzers only provide frequency and amplitude information, the network analyzers used in the Antiproton Source also provide phase information. Examples of systems that can be analyzed are coaxial cables, stochastic cooling systems, RF amplifiers and other electronic devices.

Operationally, network analyzers are most frequently used for making transfer function measurements of portions of the stochastic cooling systems. Measurements are said to be either "open loop" or "closed loop". In an open loop measurement, the network analyzer is switched into the stochastic cooling system so that the cooling system is not actually operating (the feedback loop is open). The network analyzer is used to measure how that part of the cooling system (possibly plus the beam) modified the reference signal. In a closed loop measurement, the reference signal from the network analyzer is injected into the operating cooling system (with the feedback loop closed) and a diagnostic beam pickup is used to measure the signal's effect on the beam. An applications program is used to set parameters and manipulate switches for stochastic cooling measurements.

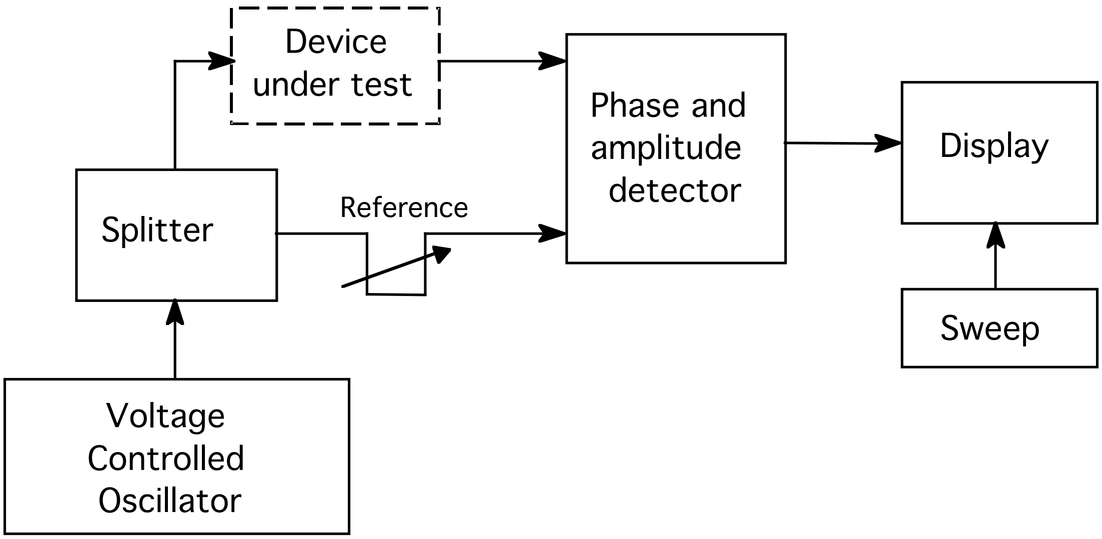

Figure 7.9 Network Analyzer

3. Dynamic Signal Analyzer

The Dynamic Signal Analyzer (DSA) is in many ways similar to a spectrum analyzer. The most noteworthy difference is the DSA's ability to produce a Fast Fourier Transform (FFT) which requires an "on-board" microprocessor. Unlike the spectrum analyzer that sweeps through a frequency range, the DSA has parallel filters, which allow simultaneous measurements across a frequency range. The disadvantage is that the DSA has a limited bandwidth over which it can produce an FFT, defined by the sample rate of the input data.

The DSA's are well suited for their use with the Pbar source's FFT because the longitudinal beam profile being measured in the Debuncher and on the Accumulator injection orbit don't significantly change frequency and have a relatively narrow frequency spread. In the original configuration, an "FFT box" was connected to a pair of spectrum analyzers and did the FFT calculations as well as providing gating for the analyzers. The spectrum analyzers were later replaced with a pair of DSA's, which do the FFT calculation. The FFT box is still used but now only provides trigger timing.

4. Vector Signal Analyzer

The Vector Signal Analyzer (VSA) is a hybrid between a DSA and a spectrum analyzer in the sense that it combines the power of digital signal processing of the DSA with the enormous frequency range and dynamic range found in a swept tune instrument. This new generation instrument attains this "hybridization" with a large parallel digital filter array at its input and, more importantly, the improvements in chip technology. The VSA has a much larger bandwidth than the DSA. The VSA could make a similar measurement for signals that changed frequency or had a large frequency spread. The VSA was developed to meet the demand for an instrument capable of measuring rapidly time-varying signals and to address problems dealing with complex modulated signals that can't be defined in terms of simple AM, FM, RF, etc.

Spectrum analyzers work very well for signals that don't vary over time, but are difficult to use in situations where the opposite is true. The Accumulator momentum profile typically displayed on CATV Pbar channel 29 provides a good "snapshot" of what the beam looks like shortly after ARF-1 has moved beam to the edge of the stacktail. It is not a true snapshot because there is a finite sweep time required to measure the signal. The signal being displayed on the low frequency side of the analyzer is sampled at a time earlier than those on the high frequency side. If one wanted to examine what took place at other times in a typical stacking cycle, the spectrum analyzer would need to be triggered at different times, although the problems related to the finite sweep time would still exist. The VSA could input the same signal and create a continuous display of the beam movement during the stacking cycle. While the spectrum analyzer could create the equivalent of sets of overlapping still photographs, the VSA would create a movie. The VSA is most frequently used for studies but is available as a diagnostic for operational problems.

K. Resistive Wall Monitor

Circulating beam with a bunch structure causes current to flow on the inside of a metallic beam pipe such as the stainless steel beam pipes used in the Antiproton Source. By breaking the metal beam pipe with an insulating ceramic gap and placing a resistor across the gap, one can measure the voltage drop across the resistor that is proportional to the beam current. There are two wall monitors in the Accumulator located in the 10 and 50 straight sections (the latter was moved from its original location in the AP2 line). The most common use of the Accumulator wall monitors is to observe the bunch structure on the beam. In collider run 1b the A10 wall monitor was used for the ARF3 feed forward system and also used to measure the longitudinal emittance of extracted beam.

The frequency response of the pickup rolls off on the low end because of beam pipe conditions external to the pickup, so the pickup is housed in a shielding box loaded with ferrite material to provide a known value of inductance. The geometry of the ceramic gap and the resistors are chosen to form a properly terminated transmission line. The low frequency response of the wall monitor is determined by the time constant set by the ferrite (16 mH) and the gap resistance (0.5Ω), it is about 5 kHz.

The characteristics of the ferrite inductors also set the high frequency response of the pickup. Two types of ferrites and a coating of microwave absorbing paint inside the shielding box are used to provide an even frequency response to 6 GHz.

As beam passes irregularities, like bellows, in the beam pipe, it induces microwave fields at frequencies determined by the dimensions of the beam pipe structures. That energy travels down the inside of the pipe and can be detected by the wall monitor. To avoid those noise problems, ferrite chokes are installed on both ends of the wall detector.

Signals are taken off the gap at four points around the circumference and summed to minimize sensitivity of the output signal to variations in beam position within the pipe. The overall sensitivity of the monitor, accounting for gap resistance, summing of the four signals, 50Ω terminating resistor, etc. is approximately 0.15Ω. That is, the transfer impedance of the pickup is the output voltage over the beam current:

$$Z_{pu} = \frac{V_{out}}{I_{beam}} = \frac{.15\mathrm{V}}{1\mathrm{A}} = .15\ \Omega$$

L. Dampers

Transverse dampers exist in the Accumulator for the purpose of damping out transverse coherent instabilities (beam wobble) at frequencies lower than that of the transverse stochastic cooling systems (2-4 and 4-8 GHz) and also for use as diagnostic tools. The dampers operate in the frequency range of 240 kHz to 150 MHz and act on much larger beam samples than the stochastic cooling does. The lower limit to the frequency response was selected to include the lowest betatron sideband, which is located at 240 kHz. The upper frequency limit of the dampers is dictated by the length of the pickup and the response of the amplifiers.

All transverse information about the beam is contained in the betatron sidebands. Since the pickups are located in a low dispersion region, there should be nearly no difference between beam position at the core vs. the injection orbit. It is important for the beam to be centered in the pickups to properly damp out oscillations. The pickups are mounted on motorized stands for centering them with respect to the beam. Signals at harmonics of the revolution frequency contain no useful information for transverse damping. Notch filters are used to reject revolution harmonic signals that could swamp the electronics during pbar extraction.

The dampers consist of pickups and kickers (both horizontal and vertical) located in a low dispersion area. The pickups and kickers are located nearly adjacent to each other, but it is actually the *next* beam turn that is corrected. Since the tune is not far from _, the beam at the kicker has oscillated nearly the ideal odd multiple of 90° away from the pickup. The damper kickers apply a correcting force on the beam by deflecting or "kicking" the beam. The pickups are 0.5m long $^1/_4$ wave radial striplines located in the A10 low dispersion straight section to reduce any possible longitudinal coupling. The pickups sense coherent betatron oscillations and the signal passes through an amplification system and an appropriate delay line to match the pickup signal to the transit time of the beam. The amplifiers are able to deliver up to 300W of power (although they normally run at 2W or less) to the 50Ω terminated $^1/_4$ wave kicker loops also located in the A10 straight section.

As a diagnostic the dampers are used to amplify transverse oscillations, or heat the beam, by driving the kickers with a white noise generator. This is useful for performing aperture measurements; beam fills the aperture and a scraper defines the edges of the beam. A reversing switch can be used to connect the damper pickups to a different set of kickers for reverse protons.

There are also dampers in the Debuncher although they are only used for studies and were never intended to be used operationally. The time that beam resides in the Debuncher is short during stacking and the intensity is low, both tend to discourage the growth of transverse instabilities. The lowest betatron sideband in the Debuncher is located at 110 kHz, which requires a different amplifier than those used in the Accumulator. The Debuncher damper system has a useful frequency band of 10 kHz to 12 MHz and a peak power output of about 100W. The Debuncher dampers do not use a notch filter as the Accumulator does.

M. Wide Band pickups

As the name implies, the wide band pickup is able to detect a relatively broadband range of frequencies as compared to other detectors. Actually the resistive wall monitors and gap monitors are also broadband but have poor response that makes it difficult to observe Schottky signals. The wideband pickups, both horizontal and vertical, are actually made up of three small $^1/_4$ wave stripline Schottky detectors. A 10-inch pickup is sensitive to signals in the .2-.4 GHz range, a 4-inch pickup sensitive to signals in the .5-1 GHz range and a 2-inch pickup sensitive to signals in the 1-2 GHz range. Each pickup is attached to hybrids that provide both sum and difference signals for viewing at AP10. All twelve signals (sum and difference signals for three horizontal and three vertical pickups) are connected to amplifiers that must be powered to provide a strong enough signal for the signal analyzers. An analyzer must be connected to the appropriate cable spigot at AP10 to select a particular frequency range, the switch tree can only be used to connect horizontal or vertical set of pickups to the appropriate analyzer.

The wide band pickups are located in the A10 straight section and are used, among other things, as the source of the signals used by the Accumulator emittance monitors. It is especially useful for measuring signals related to stochastic cooling in the 1-2 GHz range (recall that the Schottky pickups are sensitive to frequencies in the 70-80 MHz range).

N. Gap Monitor

A gap monitor is virtually identical in design to a RF cavity. In fact the gap monitor used in the Accumulator in the 10 straight section is the same style resonant cavity used for ARF2 and DRF2. Unlike a RF cavity, which has power applied to it to accelerate or decelerate the beam, as bunched beam passes through the gap in the cavity a voltage is produced.

The gap monitor is not a totally passive device, the beam is decelerated slightly as it passes through the gap (what would be the accelerating gap in a RF cavity). The amount of energy given up by the beam as it passes through the resonant cavity is determined in part by the Q of the cavity (the relative strength of the resonance). The gap monitor cavities are intentionally lower in

Q than the RF cavities. The low Q weakens the signals but reduces the effect on the beam. Although the cavities retain the ferrites used in RF applications, the capacitance is kept much lower. The gap monitor is a relatively large bandwidth device but is not sensitive enough to detect Schottky signals.

O. Flying wires

Six flying wires are used in the Accumulator to allow accurate transverse emittance and momentum distribution measurements. Five of the wires are located in a single assembly in the A40 high dispersion straight while the other wire is located in A30 between A3Q7 and A3B7 where the dispersion is relatively low. The three horizontal wires in A40 are positioned to allow separate measurements of beam on the injection orbit, central orbit and core orbit.

Each flying wire is a 25-micron carbon fiber that is held in a fork assembly and passed at velocities up to 10 m/s through the beam. The wire passing

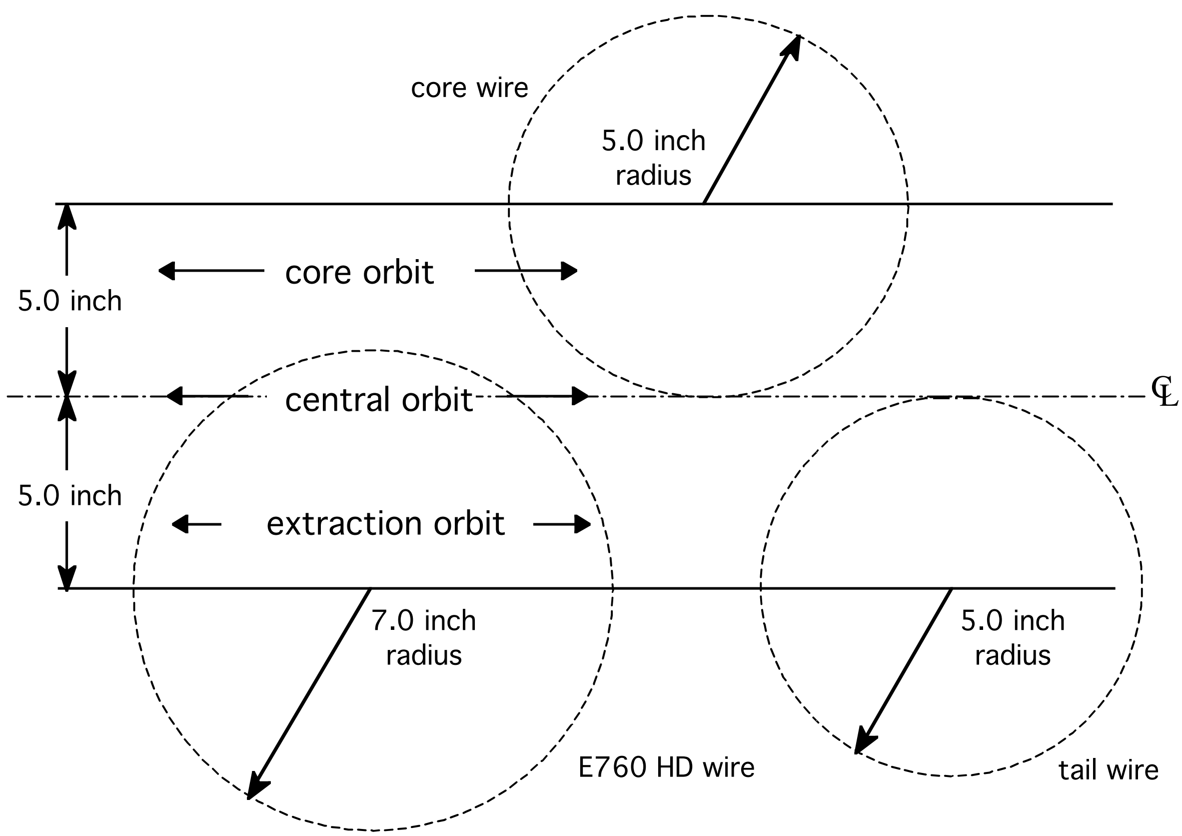

Figure 7.10 A40 high dispersion straight flying wires

through the beam creates a cascade of losses that is proportional to the beam intensity at that wire position. A paddle made of plastic scintillator is placed downstream of the wire to intercept part of the secondaries (actually there are paddles on either side of the flying wire for both proton and antiproton beams). Particles passing through the scintillator produce light that is measured with a Photo Multiplier Tube (PMT). The PMT produces a signal that is proportional to the secondaries passing through the scintillator paddle. An optical encoder on the flying wire assembly provides position information to an angular resolution of 0.022 degrees. Using the PMT output and the wire position information a beam profile can be created.

Of the five wires located in the A40 straight section there are core horizontal and vertical wires, tail horizontal and vertical wires (actually mainly used for the injection/extraction orbit), and the E760 high dispersion (horizontal) wire (for the stacktail and central orbit). By comparing beam profiles from the E760 high dispersion wire and the A30 low dispersion wire, the momentum distribution can be inferred. Figure 7.10 provides a view from above of the three horizontal wires in the A40 wire assembly.

Flying wire system hardware is located at the south end of the AP30 service building. The system is built around a Macintosh computer, which is connected to the ethernet. Motion control is supplied by a pair of NuLogic 3-axis motor controllers. A VME-based system (see figure 7.11) is used for data acquisition, the VME modules are mostly Fermilab design including clock decoders, trigger modules, digitizers and scalar cards. The flying wire software is a LabVIEW application running on the Macintosh. Communication with the computer requires either manual operation at the computer, logging in from another Macintosh or logging in from a terminal via Telnet. ACNET application program W64 is used for manipulating flying wire data and there are ACNET parameters that provide measurement and timing information.

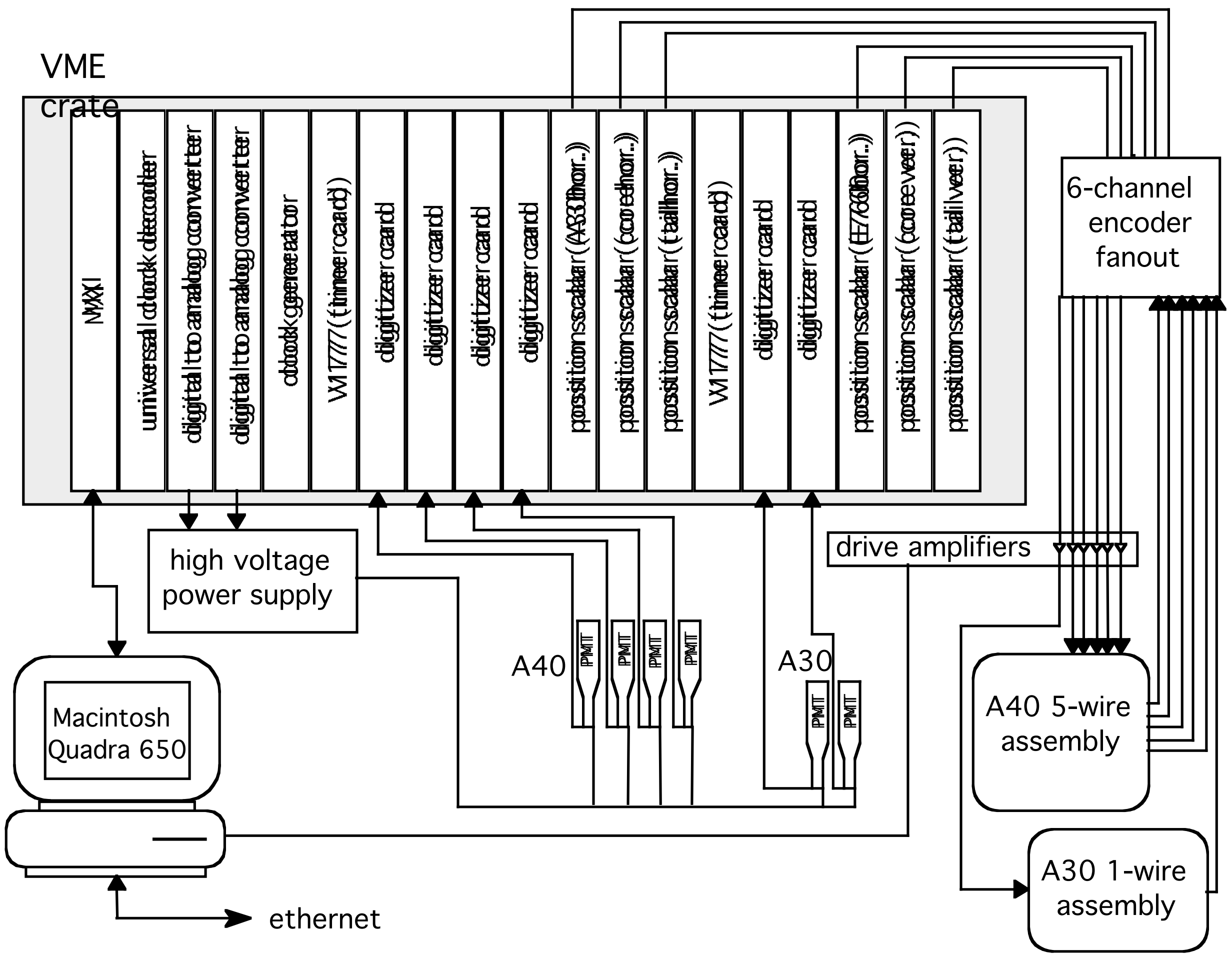

Figure 7.11 Flying wire system hardware

P. Clearing Electrodes/trapped ions

There are about 140 clearing electrodes located at various points in the Accumulator. The clearing electrodes are used to reduce the number of positive ions that are trapped in the beam. Before going into detail about the electrodes themselves, a short discussion about the trapped ions and their interaction with the antiproton beam will follow.

Residual gas in the Accumulator vacuum chamber that passes through the antiproton beam can have an electron stripped away, leaving a positive ion. The positive ions are being continuously produced as long as the antiproton beam is present. The production rate depends on the quantity and type of residual gas in the vacuum chamber as well as the beam intensity. A typical rate would be on the order of 10 E10 to 20 E10 per second for a 40 E10 stack.

In the absence of any outside influence, the number of positive ions will increase until the antiproton beam is totally neutralized.

The production process results in the ions having a small velocity and nearly all of the ions that are produced become trapped in space charge potential wells. The depth of the wells depends on the size of the beam pipe and the size of the beam envelope at a particular location. The ions will move longitudinally towards the deepest potential well that they can reach. The ions oscillate transversely in the antiproton beam, their frequency dictated, in part, by the mass and charge of the particular ion and the depth of the beam space charge potential well. About half of the ions produced are monatomic and molecular hydrogen that have lost an electron (the hydrogen outgasses from the beampipe). The oscillation frequency of the hydrogen ions happens to be close to the low order betatron resonant frequency of the beam and will therefore drive coherent oscillations of the beam. It is interesting to note that a proton (or positron) beam also creates positive ions, but they are not attracted to the beam and do not become trapped as they do with an antiproton (or electron) beam.

The net effect of having the trapped ions in the Accumulator is that the beam is very sensitive to instabilities that are driven by these ions. There is a threshold at which the combination of transverse and longitudinal beam size will result in rapid transverse emittance growth of the beam. Several colorful names, such as "motorboating" and "porpoising" have been given to this rapid growth of emittance, which often is periodic over about 30 minutes. Since the transfer efficiency of Pbar shots to the Main Ring improves as emittances are reduced the trapped ions can lead to reduced luminosity for the collider experiments. Trapped ions have another detrimental effect, which is a tune shift for the antiproton beam. This is easier to compensate for as the shift will normally be nearly constant.

The most successful strategy for mitigating problems relating to trapped ions has been to eliminate as many of the ions as possible. It is necessary to constantly remove the trapped ions as they are continuously produced and over seconds will return to fill the potential wells. The greatest reduction in trapped ions has come from the use of clearing electrodes. Originally the clearing electrodes were a few select Beam Position Monitor pick-ups which had a -100 Volt potential applied to them. An upgrade was put in place in Collider run 1a which included expanding the number of clearing electrodes and increasing the potential to –1,000 Volts. Dedicated clearing electrodes were added to locations such as stochastic cooling tanks, which did not have BPM's in close enough proximity.

There are still locations, such as in the middle of the bending magnets, where a clearing electrode cannot be located. Another method for dislodging the trapped ions is bunching the beam with RF. Only 10-20 volts of RF is enough to significantly reduce the population of trapped ions in the Accumulator, additional RF provides little additional benefit. By bunching the beam some of the trapped ions can be flushed from the potential wells they reside in. The ions that are dislodged appear to be forced into the vacuum chamber walls instead of being pushed towards the clearing electrodes for removal. It is believed that the clearing RF is not as effective for clearing heavy ions, which means that some of the cleared hydrogen atoms will be replaced by the heavier, less harmful ions. If the stabilizing RF is removed, it may take several minutes for the trapped hydrogen ions to return to the equilibrium level maintained in the absence of the RF. ARF-2 has traditionally been used to provide the "stabilizing RF" for the Accumulator.

The combination of clearing electrodes and stabilizing RF has resulted in a lower critical threshold of emittances for ion induced instabilities. This threshold is lower than the cooling systems can achieve for even the largest stack sizes to date. Smaller emittances and momentum spread have allowed efficient transfers to be made to the Main Ring with stacks in the 200 E10 range.

Q. Quadrupole Pick up

The quadrupole pick up is located in the Accumulator at the upstream end of the A10 straight section and is used to measure transverse quadrupole oscillations of the beam. There is also a skew-quadrupole pickup located next to the "normal" quad pick up but it has been rarely used. The pickups are about a meter in length and are made up of four striplines. The quad pick up has the striplines oriented vertically and horizontally on either side of the beam, the skew quad pick up has the striplines rotated 45°. The signals are amplified then sent to electronics in the AP-10 service building, which processes the signals. Vertical, horizontal, sum and quadrupole signals are available for use.

Unlike dipole oscillations, which arise from steering errors, quadrupole oscillations are the result of lattice (ß function) mismatches between an accelerator and associated beamline. Typically the quad pick up would be connected with a digital oscilloscope to view the signal. The primary use of the pick up to this point has been to attempt to quantify the lattice mismatch between the AP-3 line and the Accumulator. In principal, the match can be improved by varying AP-3 quadrupole currents and observing and minimizing the amplitude of the quadrupole oscillations from protons reverse-injected from the Main Ring. In practice the quadrupole signals are swamped by the dipole signals. The pick up could be used to detect quadrupole instability signals or work as a quadrupole damper, but it's not presently set up that way.

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